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INFLUENCE OF GRAVITO-INERTIAL FORCE
ON VESTIBULAR NYSTAGMUS IN MAN

18

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bular nystagmus in man

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ABSTRACT

The influence of high +Gz gravito-inertial force (— G load) on the vestibular system in man has been investigated in a centrifuge with a freely swinging gondola. The vertical vestibular nystagmus induced by acceleration to 3G was analysed, and compared with reference measurements at 1G. Our results indicate that the effects of increased G load are expressed in a prolonged time contant of the upbeat nystagmus, and in a subject-dependent persisting component of this nystagmus.

In an attempt to explain these findings, a current model on the generation of vestibular induced eye movements is extended:
Angular acceleration stimulates the semicircular canals, which in an existing model induce slow compensatory eye movements via a direct reflex path, as well as through an integrating network in the central vestibular nuclei. This model is extended with the G load as a stimulus function for the otoliths, which are influencing eye movements via a direct path, as well as through a modulating action on the central integrator.

This influence of G load on the vestibular system could interfere with visual perception, and thereby play a role in inducing spatial desorientation. Nother le : it. (AU)

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                                                      Soesterberg

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Invloed van hoge +G, gravito-inertiaal kracht op de vestibulaire
nystagmus bij de mens

J.T. Marcus

SAMENVATTING

De invloed van hoge +Gz gravito-inertiaal kracht (= G kracht) op het
vestibulaire systeem van de mens is onderzocht in een centrifuge
werkend met een vrij uitzwaaiende gondel. De verticale vestibulaire
nystagmus geïnduceerd door acceleratie naar 3G werd geanalyseerd, en
vergeleken met referentiemetingen bij 1G. Onze resultaten geven aan
dat de effecten van toegenomen G-belasting tot uiting komen in een
verlengde tijdconstante van de nystagmus met snelle slag naar boven,
en in een proefpersoonafhankelijke blijvende component van deze
nystagmus.
     In een poging om deze bevindingen te verklaren, wordt de gene-
ratie van vestibulair geïnduceerde oogbewegingen modelmatig beschre-
ven:
De hoekversnelling stimuleert de halfcirkelvormige kanalen, die
volgens een gangbaar model langzame compensatoire oogbewegingen
induceren zowel langs een directe reflexbaan, als via een integrerend
netwerk in de centraal vestibulaire kernen. Dit model wordt uitgebreid
met de G-belasting als stimulusfunctie voor de otolieten, die de
oogbewegingen beïnvloeden zowel langs een direct pad als via een
modulerende werking op de centrale integrator.
     Deze invloed van G-belasting op de evenwichtszin zou de visuele
waarneming kunnen verstoren, en een rol kunnen spelen bij het ontstaan
van ruimtelijke desoriëntatie.

1   INTRODUCTION

Flight maneuvres in high performance aircraft are capable of genera-
ting high acceleration forces. The effects of these forces on the
vestibular system are still largely unknown.

The aim of the present study is to evaluate the influence of
sustained high +Gz gravito-inertial force (= G load) on the vestibu-
lar system. 1 G denotes the amplitude of gravity force in the absence
of centrifugal forces, and the index z refers to the subject's head
to foot axis.

Previous reports indicate that increased G-load enhances the vestibu-
lar sensitivity: Gilson et al. (1973) observed that subjects
perceived illusory changes in aircraft attitude, during and after
head movements in a 2 G bank and turn. These shifts in apparent
orientation are attributed to a G-excess effect. Gillingham and Wolfe
(1986) described the mechanism of the G-excess illusion by analysing
the displacement of the otolithic membranes during increased G-load.
DiZio et al. (1987) reported an increased sensitivity to Coriolis
stimulation during the 2 G phase of parabolic flight.

These observations cannot be explained completely with current models
of the vestibular system, which do not include variations in G-load.
In our experiment the vestibular function was evaluated by investi-
gating the vertical nystagmus induced by the movement of a centrifuge
gondola. These eye movements could have practical implications:
incomplete suppression will lead to impaired visibility of instru-
ments.

2   GENERATION OF +G$_z$ GRAVITOINERTIAL FORCE

2.1   +G$_z$ force in the centrifuge

The +G$_z$ acceleration was generated by means of a centrifuge with
radius of 4 m, located at the National Aerospace Medical Center,
Soesterberg, The Netherlands. The centrifuge has a freely swinging
gondola, so that the test subject within the gondola experiences a z-
axis acceleration that is aligned with the resultant of the
centripetal and gravitational accelerations. This is called a coordi-
nated turn.

The computer-controlled G profile was:

orbit	1.05 G_z	for 1 min
acceleration	+0.1 G_z/s	
sustained	3 G_z	for 2 minutes
deceleration	-0.1 G_z/s	
orbit	1.05 G_z	for 1 min.

The orbit interphase has been applied in order to reduce the Coriolis stimulation in acceleration and deceleration due to the swing movement of the gondola. At 1.05 G_z the gondola swing angle in roll is already: arccos (1/1.05) = 17.75 dg.

Nine naive volunteers were exposed to this profile. Prior to the experiment, routine medical examination was performed and the subjects were made familiar with the experimental conditions. The subject wore an anti-G suit, and his head was supported in each of these positions: upright, 40 dg backward, and 90 dg backward. Eye movements were registered by means of infrared photodiodes and phototransistors (Reulen et al. 1988), in complete darkness as well as with visual fixation.

A pilot study was performed on a rotating chair, with the subjects (n=10) lying on their side to stimulate the vertical semicircular canals. The rotation profile was: acceleration at 5 dg/s^2 to an angular velocity of 90 dg/s that was maintained for 90 s before deceleration at 90 dg/s^2.

2.2 +G$_z$ force in an aircraft

In an aircraft the +G_z force is generated with a linear velocity that is considerably higher than in the centrifuge. As a consequence, the angular velocity in the aircraft is significantly less than in the centrifuge, when the same G profile, as applied in the centrifuge, is generated in the air.

In Table I a 3G_z coordinated turn is described for the centrifuge, and an aircraft with air speed 150 kts; r = radius, v = linear velocity, v^2/r = centripetal acceleration [m/s^2] and v/r = angular velocity [rad/s]. In the Table angular velocity is converted to dg/s.

Table I   Comparison of a $3G_z$ coordinated turn in centrifuge and aircraft.

	radius [m]	velocity [m/s]	angular velocity [dg/s]
centrifuge	4	10.53	151
aircraft	214	77	21

Therefore high G turns in an aircraft experiment will provide further evidence for pure G effects on the vestibular system, because the angular velocity is not as dominant as in the centrifuge. Vertical nystagmus was measured in 3 subjects during a $3G_z$ level bank and turn; air speed was 150 kts (1 knot − 1.85 km/h).

3   VESTIBULAR NYSTAGMUS DATA

Our findings on the vertical vestibular nystagmus in the centrifuge included:
(1) The upbeat nystagmus induced by the angular acceleration to $+3G_z$ had a longer decay time constant in slow phase velocity (spv), than the downbeat nystagmus after deceleration to $+1G_z$.
(2) In 6 subjects a persisting upbeat nystagmus was observed during the $+3G_z$ load at constant angular velocity of the centrifuge. In pilot studies this nystagmus extended for up to 5 min.

Data from one subject are presented in Fig. 1, showing the G load and the vertical eye position over time. Note that the upbeat nystagmus was still present at the end of constant G load, and that its direction was reversed during deceleration.

A nystagmoid eye movement is composed of a slow compensatory phase, induced by the vestibular system, and a fast phase induced by the saccadic system in order to bring the eyes back in neutral position. This study is focussed on the output of the vestibular organs; therefore the nystagmus slow phase velocity (− spv) is derived from the eye position data which are partly presented in fig 1.
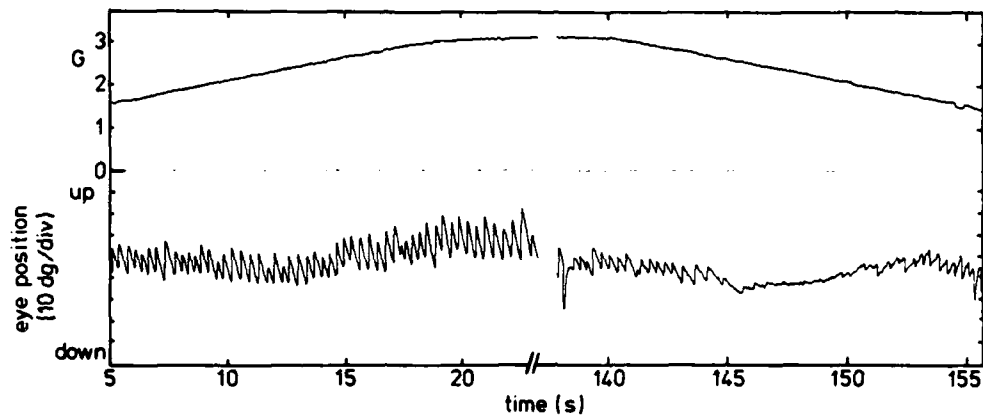
Fig. 1   Plots of G_z and the vertical eye position signal in a 1-3-1G_z centrifuge run in acceleration and deceleration phases. A sustained 3G load was applied for 2 min. Note that the upbeat nystagmus was still present after 2 min. During deceleration the direction of nystagmus was reversed.

Fig. 2 shows the nystagmus spv calculated from the eye-position signal. The noise in the spv signal, prior to and after the G run, was caused by the normal resting activity in the eye movements.
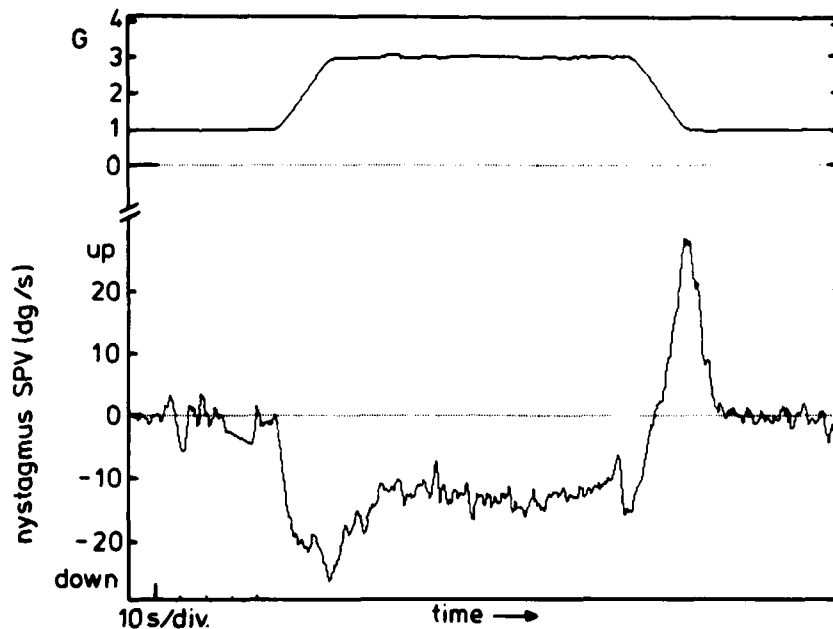
Fig. 2 Plots of G_z and the vertical nystagmus slow phase velocity (spv), corresponding with the dataset in Fig. 1. Note that the time constant of recovery from the upbeat nystagmus during $3G_z$ is longer than for the downbeat nystagmus after deceleration to $1G_z$. The persisting vertical upbeat nystagmus during the $3G_z$ load has a magnitude of about 10 dg/s.

The nystagmus time constant, T_c, was determined by fitting an exponential of the form spv = A*exp(-t/T_c) to the decaying part of the slow phase velocity, using the algorithm described by McFall et al. (1986). The spv of the sustained nystagmus was subtracted from the data prior to calculating the best fit equation. In Table II the computed values of T_c for the acceleration and deceleration phases are presented. Two subjects were exposed to a different G profile, so the time constants for their responses are not included.

Table II Decay time constant of vertical nystagmus induced by centrifuge acceleration from 1 to $3G_z$, and deceleration from 3 to $1G_z$. A "+" indicates the observation of persisting upbeat nystagmus during the $3G_z$ load.

Subjects	Head position backw. [dg from vertical in sagittal plane]	Time constant from 1 to $3G_z$ [s]	Persist. during $3G_z$	Time constant from 3 to $1G_z$ [s]
kre	40	10.8	+	7.5
kre	90	8.5	+	8.0
ott	90	13.3	+	10.3
vos	90	10.6	+	7.9
mag	0	12.6	+	8.7
mag	90	10	-	9.7
gra	0	17.8	-	3.5
gra	40	21.1	+	3.6
gra	90	15.5	+	7.3
vee	0	27	+	4.8
vee	40	7.4	+	3.1
vee	90	21.1	-	5.6
ble	0	13	+	13.4

Application of a sign test results in the conclusion that the time constant after G onset is longer than after G offset, with $p < 0.005$. Suppression of the vertical nystagmus could be achieved by fixation on a stationary visual target within the gondola. However, during G onset and G offset this suppression was not complete, and nystagmus amplitude amounted up to 5 dg/s in spite of visual fixation. Dependence on pitch head position has not been found so far.

A prolonged decay time constant is observed after G onset, when comparing it with the decay after G offset with the same rate. Before this can be attributed to the G load, the first to check is the symmetry between up-and downbeat nystagmus.
When the subject in the centrifuge is facing forward with respect to the direction of rotation, then an upbeat nystagmus is generated at G onset, and a downbeat at G offset. If there would exist a physiological asymmetry with the upbeat nystagmus inherently longer during than the downbeat, then the observed prolongation of time constant after g onset is no G effect, but merely an expression of this natural asymmetry.

The up-down symmetry of vertical nystagmus at 1G was therefore inves-
tigated by positioning subjects on their side on a rotating platform.
More detailed analysis will be presented in the near future.

The results of the pilot study on the rotating platform were:
(1) No asymmetry in vertical upbeat or downbeat nystagmus was ob-
    served.
(2) The decay time constant of vertical nystagmus was in the order
    of 4 s.
(3) The duration of nystagmus coincided with the duration of motion
    perception.

These data indicate no physiological up-down asymmetry; the observed
prolongation and sustained component of upbeat nystagmus in the
centrifuge should therefore be attributed to the Gz load. In
addition, vertical nystagmus could give information about the
subject's motion perception.
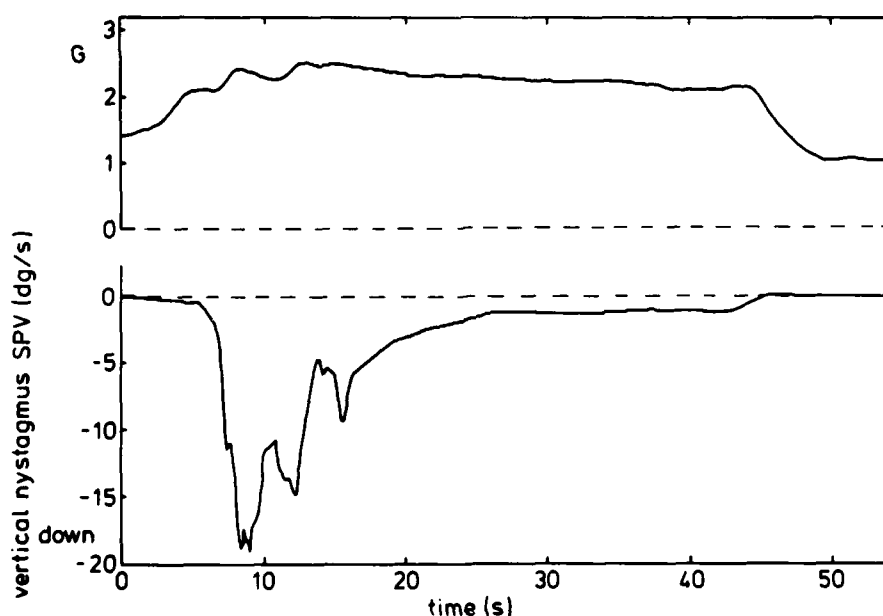
Fig. 3   Gravity load and vertical nystagmus slow phase
velocity (spv) observed in a Beaver aircraft during a co-
ordinated turn with a maximum load of $2.6G_z$. Peak angular
velocity in the pitch semicircular canal amounts to about
16 dg/s. Note the persisting vertical upbeat nystagmus
during the G load, and the absence of downbeat nystagmus
during G offset. Data are from the same sensitive sub-
ject, whose response in the centrifuge is shown in Figs.
1 and 2.

Further evidence for pure G effects can be found by flying the centrifuge G profiles in an aircraft: a G stimulus with considerably less angular acceleration (see table 1). Peak G load in this aircraft run was 2.6 G with air speed 150 kts, corresponding with angular velocity of 17.5 dg/s, and angular velocity in the pitch semicircular canal of 16.1 dg/s. The persisting upbeat nystagmus was observed in one of the 3 subjects tested; see fig. 3. In the other subjects registration failed due to motion sickness, or a technical problem. Although the measurement refers to one subject, it does confirm the existence of a pure G induced upbeat nystagmus in sensitive subjects.

4   OTOLITH MODULATION OF THE VESTIBULO-OCULAR REFLEX ARC

4.1   The velocity storage model

In order to evaluate the observed characteristics of vertical nystagmus in the centrifuge, the processing of angular velocity information was computer-simulated on the basis of the velocity storage model (Raphan et al., 1977; Cohen et al., 1977; Raphan et al., 1979).

The questions to be answered by means of model simulation were:

(1) Is the prolonged duration of nystagmus induced by acceleration, compared with deceleration, merely an effect of the non-linear angular acceleration trajectory of the stimulus to the vertical semicircular canals?

(2) Could the sustained vertical nystagmus under gravity load be explained by otolith stimulation, either by a direct path from the otoliths to the oculomotor system, or by a conditioning effect on the discharge time of the velocity storage mechanism?

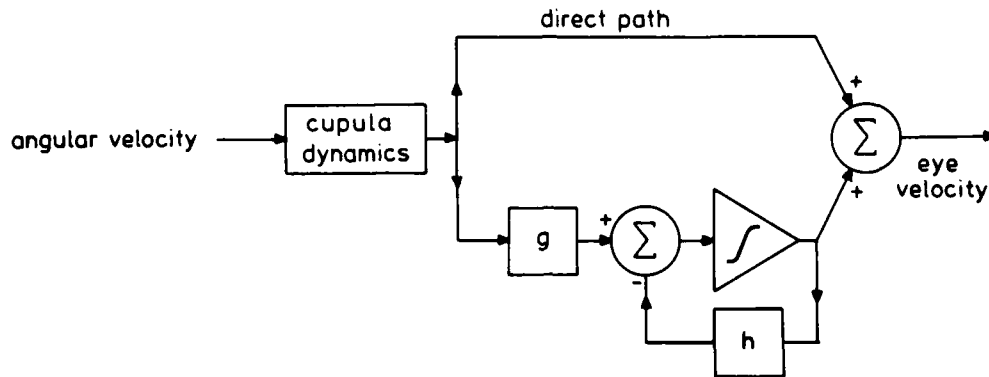In Fig. 4 the vestibular branch of the model is presented:

Fig. 4   The velocity storage model for the vestibular
nystagmus (Raphan et al., 1979). The cupula dynamics are
presented in more detail in Appendix B and Fig. 8. The
cupula deflection signal is transmitted over the direct
vestibular pathway, and is also coupled to the central
integrator via the forward gain element g; the integrator
discharges via the feedback gain element h. Values used
in the model are h - 0.15 and g - 0.2. In the model
calculations for the vertical nystagmus, the head velo-
city input was the pitch angular velocity profile in the
centrifuge (Appendix A).

The head velocity input will be the pitch angular velocity profile,
which can be calculated for the coordinated turn of the centrifuge
gondola, based on the linear G profile of 0.1 G_z/s (Appendix A). De-
tails of cupula dynamics are given in Appendix B. The slow compen-
satory phase of nystagmus is generated by the sum of two components:
a direct pathway from the semicircular canals, and an indirect path-
way through an integrator or storage mechanism localised in the cen-
tral vestibular nuclei. It is assumed here that a similar storage
mechanism is utilized in generating vertical as well as horizontal
nystagmus. The value of the feedback gain element for vertical nys-
tagmus is estimated to be h - 0.15. Displayed in Fig. 5, from above
downwards, are: the stimulus function, the model predictions for the
cupula dynamics, the central integrator, and the resulting slow phase
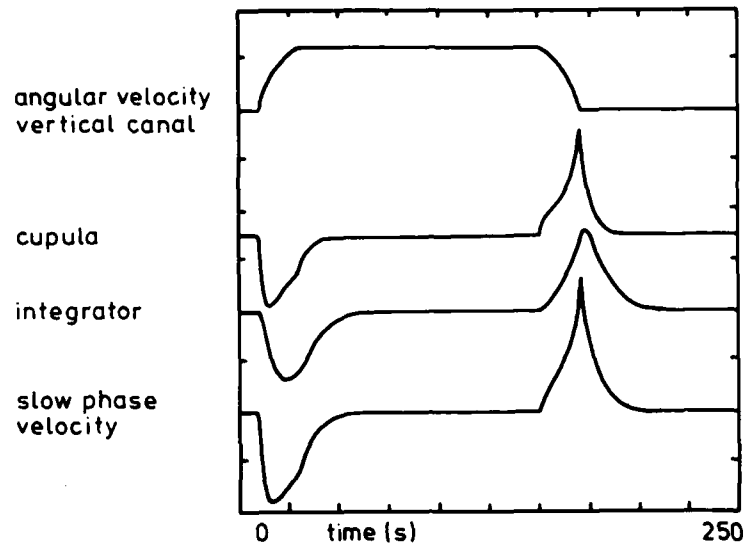velocity.

Fig. 5 Model predictions evaluated by means of the velocity storage model in Fig. 4, during a 1-3-1G$_z$ centrifuge run with linear onset and offset rates of 0.1 G$_z$/s. Note the non-linear angular velocity profile of the stimulus to the vertical semicircular canals (upper trace). The output is displayed from: the cupula dynamics, the central integrator, and the final summator which determines the nystagmus slow phase velocity (spv). It is shown that during deceleration the peak outputs from cupula and integrator almost coincide, resulting in maximal spv induction during G offset.

The high nystagmus amplitude during G onset and G offset is caused by the angular acceleration and deceleration respectively of the centrifuge, and thereby initiated by semicircular canal stimulation. During deceleration the cupula gets its peak stimulation when it is already deflected, resulting in a sharply peaked response. In addition, during deceleration the outputs from cupula and integrator reach their maxima almost simultaneously, resulting in a maximum nystagmus generation during deceleration in the downbeat direction.

4.2 Extension of the model with an otolithic contribution

These model calculations however, do not predict a prolonged nystagmus time constant during G load on the basis of canal output alone. Neither is a persisting nystagmus predicted during steady G load, because the angular velocity is constant. Because the otoliths are the

sensors for linear acceleration, an extension of the velocity storage model is proposed in which an input from the otoliths make a contribution: see Fig. 6. Gravity acts as a second component of the stimulus function. A simplified model for otolith dynamics is presented in Appendix B.
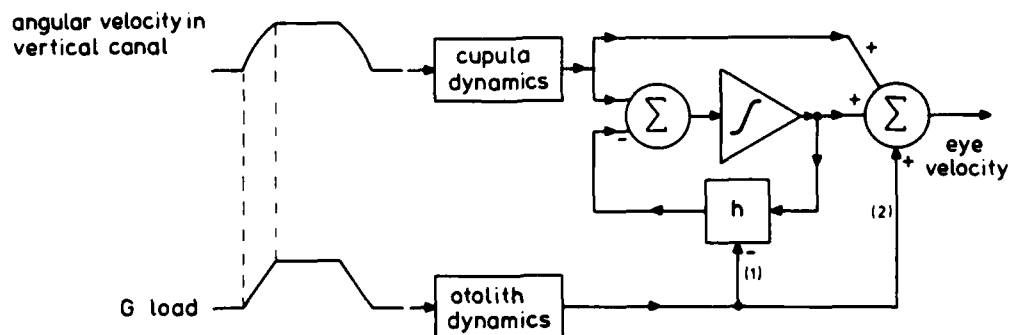

Fig. 6 Extension of the velocity storage model with gravity load as a second component of stimulus function. The gravity signal enters the otolith dynamics, and is then transferred to nystagmus velocity with the slow phase in downward direction (2). Otolith output also influences the feedback factor in the central storage integrator, leading to a prolonged time constant (1).

It is suggested that the direct otolith path (2) is responsible for generating the persistent nystagmus component during the G load. However, in order to explain the asymmetry between acceleration and deceleration response another mechanism must be added. It is proposed that the otoliths modulate the feedback gain element h of the central storage integrator and consequently the discharge time constant 1/h. Displayed in Fig. 7 are: angular velocity in vertical canal, gravity load, output of central integrator and resulting spv. Cupula output is the same as in Fig. 5.
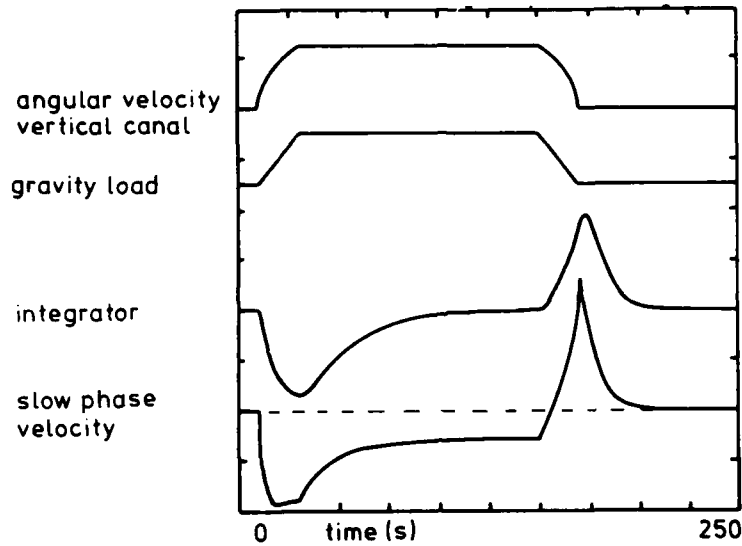
Fig. 7 Model predictions of the velocity storage model
with gravity load as a second stimulus function. Cupula
output, not shown in this plot, is identical to that in
Fig. 5. The differences with the spv trace in Fig. 5 are:
an increased decay time constant during the G load, and a
persisting component. This results in a better approxima-
tion of the centrifuge data presented in Fig. 2.

Comparison of the spv model prediction in Fig. 7, and the spv data in
Fig. 2, indicates that the extended model can account for both the
asymmetry in spv response and the sustained nystagmus at constant vel-
ocity.

5   DISCUSSION

Previous studies have been devoted to potential physiological asymme-
tries in vertical eye movements: Matsuo et al. (1979) observed an
asymmetric velocity storage for upward and downward nystagmus in
monkeys: the amount of stored activity was always weaker for upward
than downward nystagmus. However, if a similar asymmetry exists in
man, it cannot explain our finding of a prolonged upbeat nystagmus.
    Baloh et al. (1986) found no significant difference between the
mean gain of up and down slow eye movements induced by vestibular,
visual or visual-vestibular stimulation in a group of normal human
subjects. This is in agreement with the results of our pilot study on

the rotating chair. Thus it may be concluded that there is no evidence for a physiological up-down asymmetry in vertical eye movements in man, that could explain the differences between the responses found during acceleration and deceleration of the centrifuge in the present study.

Matsuo and Cohen (1984) observed in monkeys that the otolith organs suppress velocity storage for the downbeat nystagmus in the upright position; the relationship of optokinetic afternystagmus to head position suggests that the otoliths exert a conditioning effect on the discharge time constant of the central integrator. This seems to be quite in agreement with the proposed indirect otolithic pathway in Fig. 7, where the otolith output controls the feedback gain element h in the central integrator.

6   IMPLICATIONS FOR THE AVIATOR IN HIGH PERFORMANCE AIRCRAFT

The findings on vertical nystagmus during a coordinated high G turn have practical significance: Baloh et al. (1986) reported that vertical nystagmus is difficult to suppress by visual fixation, especially in the downbeat direction. In our study, suppression of nystagmus by fixation was only partial during G onset and offset. The degree of suppression might be even less when the visual target is not as clearly defined, e.g. during visual scanning of instruments, or during a visual search task.

In high performance aircraft both the G onset rate and the level of $3G_z$ used in our experiment, are often largely exceeded, which means that even stronger nystagmoid eye movements are to be expected in flight. Recent modelling of the otolith mechanics indicates that the sensitivity of the system extends over a large range of shear force, due to an increased stiffness of the gelatinous layer with continued deflection (Grant and Best, 1987).

Vestibular stimulation in a high G environment could therefore have a major impact on pilot task performance in two aspects:
(1) Incomplete suppression of nystagmus will lead to impaired visibility of instruments, and consequently to a decrement in the aviator's ability to perform those tasks where visual displays are of prime importance. Benson and Guedry (1971) described a correlation between the error in a tracking task and nystagmus spv.
In addition to the blurring effects of nystagmus, Lentz and Guedry (1982) observed an apparent deflection of instrument horizon during and after rolling maneuvers. Because the aviator

is not aware of nystagmus, the tracking of an image on the retina during the slow phase could be perceived as object motion.

(2) An alteration of the dynamics of the vestibular system during G load could increase the aviator's susceptibility to spatial disorientation, and the likelihood of loss of control in flight. If, as the experimental evidence suggests, the discharge time constant of the storage integrator is prolonged by an increased G load, it could influence the perception of attitude and motion during high G maneuvers.

The vestibular perception is expected to have a higher weight in conditions where visual references are poor or even misleading, e.g. during high speed aircraft maneuvers at night.

7   CONCLUSIONS

Our findings indicate that the vestibular effects of a $3G_z$ load are manifest by an increased time constant of vertical nystagmus, and by a persistent, subject-dependent, upbeat nystagmus. An extension of the velocity storage model is proposed, with pathways from the otoliths to neural centres that generate slow phase eye movements. The otolithic contribution is composed of a direct path, and a modulation of the discharge time constant of the central integrator. The extended model is described here as the modulation model.

REFERENCES

Baloh, R.W., Honrubia, V., Yee, R.D. and Jacobson, K. (1986). Vertical visual-vestibular interaction in normal human subjects. Exp. Brain Research 64, 400-406.

Benson, A.J. and Guedry, F.E. Comparison of tracking task performance and nystagmus during sinusoidal oscillation in yaw and pitch. Aerospace Medicine, June 1971.

Boumans, L. (1982). The human VOR, effects of adaptation, Thesis Erasmus University, Rotterdam.

Cohen, B., Matsuo V. and Raphan, Th. (1977). Quantitative analysis of the velocity characteristics of optokinetic nystagmus and optokinetic afternystagmus. J. Physiol. 270, 321-344.

DiZio, P., Lackner, J.R. and Evanoff, J.N. The influence of gravito-inertial force level on oculomotor and perceptual responses to Coriolis, cross coupling stimulation. Aviation, Space and Environmental Medicine, September 1987.

Gillingham, K.K. and Wolfe, J.J. Spatial Orientation in flight. USAF School of Aerospace Medicine , Brooks AFB, TX, USA, December 1986.

Gilson, R.D., Guedry, F.E., Hixson, W.C. and Niven, J.I. Observations on perceived changes in aircraft attitude attending head movements made in a 2-G bank and turn. Aerospace Medicine, January 1973.

Grant, W. and Best, W. Otolith-organ mechanics: lumped parameter model and dynamic response. Aviation, Space and Environmental Medicine, October 1987.

Hosman, R.J.A.L.S. and van der Vaart, J.C. (1978). Delft University Technical Report LR - 265.

Lentz, J.M. and Guedry, F.E. Apparent instrument horizon deflection during and immediately following rolling maneuvers. Aviation, Space and Environmental Medicine, June 1982.

MacFall, J.R., Riederer, S.J. and Wang, H.Z. An analysis of noise propagation in computed T2, pseudodensity, and synthetic spin-echo images. Medical Physics 13 (3), May/June 1986.

Matsuo, V., Cohen, B., Raphan, Th., de Jong, V. and Henn, V. (1979). Asymmetric velocity storage for upward and downward nystagmus. Brain Research 176, 159-164.

Matsuo, V. and Cohen, B. (1984). Vertical optokinetic nystagmus and vestibular nystagmus in the monkey: up-down asymmetry and effects of gravity. Exp Brain Research 53, 197-216.

Mayne, R. (1974). A systems concept of the vestibular organs. In: Handbook of sensory physiology, vol. VI, part 2, p. 530, ed. H.H. Kornhuber.

Reulen, J.P.H., Marcus J.T., Koops, D., de Vries, F.R., Tiesinga, G., Boshuizen, K. and Bos J.E. (1988). Precise recording of eye movement: the IRIS technique Part 1. Med. & Biol. Eng. & Comput. 26, 20-26.

Raphan, Th., Cohen, B. and Matsuo, V. A velocity-storage mechanism responsible for optokinetic nystagmus (OKN), optokinetic after-nystagmus (OKAN) and vestibular nystagmus. In: Control of gaze by brain stem neurons, Developments in Neuroscience, Vol 1, edited by Baker and Berthoz, Elsevier Biomedical Press, 1977.

Raphan, Th., Matsuo, V. and Cohen, B. (1979). Velocity Storage in the Vestibulo-ocular reflex arc. Exp. Brain Research 35, 229-248.

APPENDIX A Angular Velocity in the Vertical Semicircular Canal (=
pitch angular velocity) During Linear G Onset in a Coor-
dinated Turn

Definitions

R	= turn radius	[m]
g	= gravity acceleration = 9.8	$[m/s^2]$
c	= G onset rate	[g/s]
omega	= angular velocity centrifuge	[rad/s]
alfa	= gondola swing angle in roll	[rad]
omegp	= angular velocity in vertical semic. canal	[rad/s]
G_z	= normal G load in centrifuge gondola	$[m/s^2]$
Acf	= centripetal acceleration	$[m/s^2]$

Conditions (pascal notation)

Coordinated turn	: G_z	= sqrt(g*g + Acf*Acf)	(1)
	Acf	= omega*omega*R	(2)
	alfa	= arccos(g/G_z)	(3)
Linear G profile	: G_z	= g*(1+c*t)	(4)
Swing in roll	: omegp	= omega*sin(alfa)	(5)

Derivation

of omegp with R=4:
Subst. (4) and (2)
    in (1) : omega = 0.5*sqrt[sqrt{g*g*c*t*(2+c*t)}]   (6)
Subst. (4)
    in (3) : alfa   = arccos{1/(1+c*t)}   (7)
Finally, subst. (6) and (7) in (5) yields omegp.

APPENDIX B

Model of the Otoliths, simplified (Hosman and van der Vaart, 1978)

$$\ddot{y} = \ddot{x} - \frac{r}{m}\dot{y} - \frac{k}{m}y$$
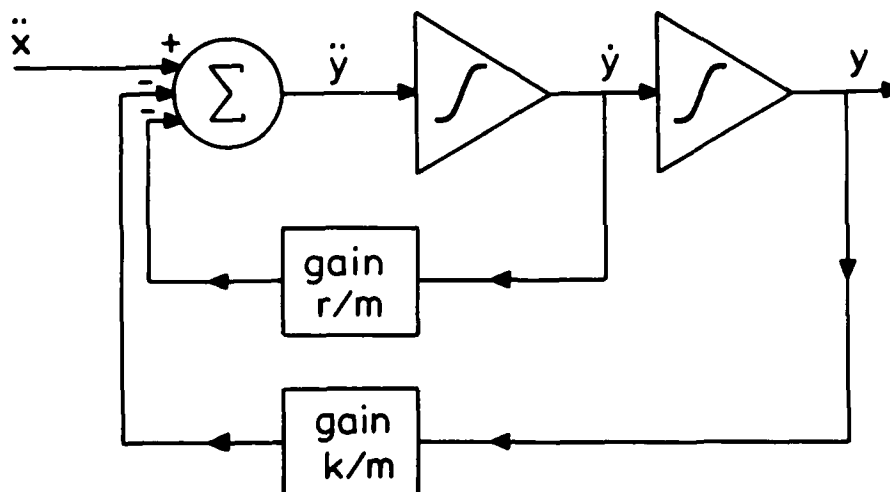

Fig. 8a Approximate model of otolith dynamics, applied in the model calculations. The system is described by a second order model, with a deflection signal as output. Feedback terms are the viscous damping r/m and the elastic torque k/m.

$\ddot{x}$ — acceleration of the head
m — mass of otolith
r — viscous damping coefficient
k — spring stiffness
y — displacement of the otoconia relative to the macula

Numerical values (Mayne, 1974): (r/m) — 1.69 [1/s]; (k/m) — 0.285 [1/s^2].

The notation $\ddot{x}$ as input is used for compatibility with existing models in literature, although in the present case of gravitoinertial force the input (with dimension force per unit mass) is not produced by second derivative of an x.

Model of Cupula-endolymph Dynamics, simplified (Boumans, 1982):

$$\ddot{\Theta}_c = \ddot{\Theta}_h - \frac{B}{I}\,\dot{\Theta}_c - \frac{K}{I}\,\Theta_c$$
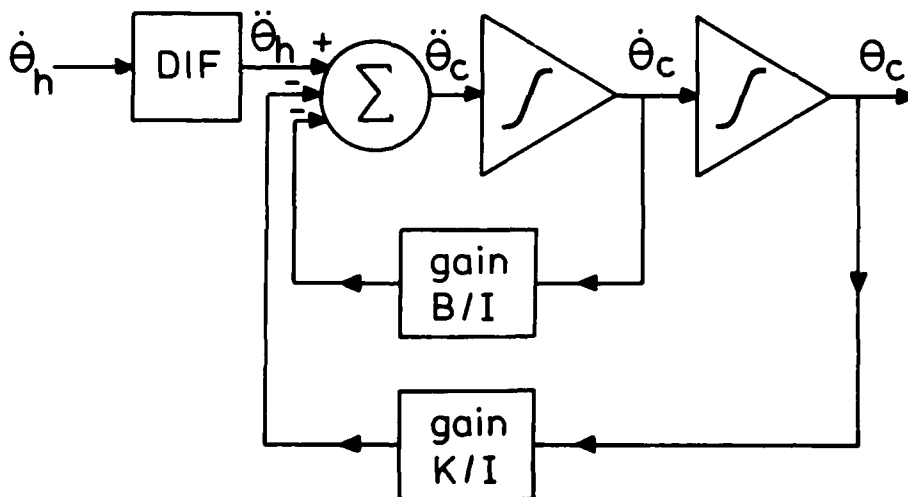

Fig. 8b Approximate model for the cupula-endolymph system, applied in the model calculations. Input is angular velocity of the head, output is cupula deflection. Feedback terms in the second-order system are the damping torque B/I and elastic torque K/I.

Θ_h — angular displacement of the head
Θ_c — angular displacement of the cupula
I — moment of inertia of the endolymph
B — damping torque,determined by the viscosity of the endolymph
K — elastic torque, determined by the stiffness of the cupula.

Numerical values: (B/I) — 50 [1/s]; (K/I) — 10 [1/s^2].

APPENDIX C Final model in a TUTSIM diagram

Fig. 9 TUTSIM blockdiagram of the extended velocity
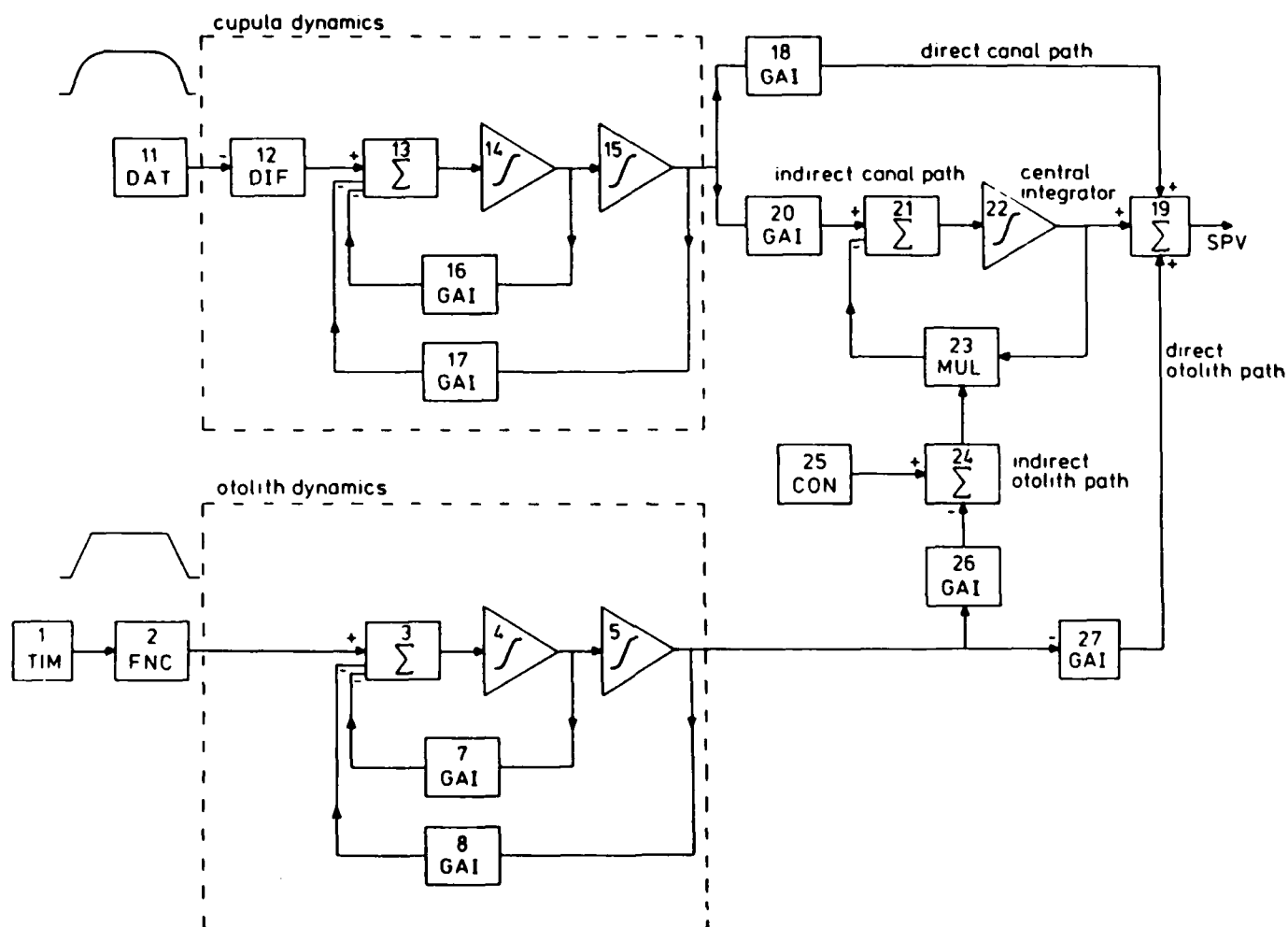storage model presented in Fig. 6. For a given G_z
profile, the angular velocity of the vertical
semicircular canal was calculated in advance and written
to a file, which is led into the cupula dynamics by means
of the "DAT" block. The corresponding G_z profile is
programmed in the function generator block "FNC", and led
into the otolith dynamics by activating the timer TIM.

APPENDIX D Programs (listings are available on request)

Name   Function

T3.SIM   TUTSIM model listing, corresponding to Fig. 9.
CENTR3.FOR Calculation of centrifuge dynamics, and the angular
            velocity in the vertical semicircular canal.
            Note: Time resolution and output-format *must* confirm to
            the TUTSIM model. Format: see label 90.
FITEXP.FOR Fitting an exponential of the form spv = A * exp($-t/T_c$).
READVES.FOR Calculation of nystagmus spv.

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Influence of gravito-inertial force on vestibular nystagmus in man

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The influence of high +Gz gravito-inertial force (= G load) on the vestibular system in man has been investigated in a centrifuge with a freely swinging gondola. The vertical vestibular nystagmus induced by acceleration to 3G was analysed, and compared with reference measurements at 1G. Our results indicate that the effects of increased G load are expressed in a prolonged time constant of the upbeat nystagmus, and in a subject-dependent persisting component of this nystagmus.
In an attempt to explain these findings, a current model on the generation of vestibular induced eye movements is extended: angular acceleration stimulates the semicircular canals, which in an existing model induce slow compensatory eye movements via a direct reflex path, as well as through an integrating network in the central vestibular nuclei. This model is extended with the G load as a stimulus function for the otoliths, which are influencing eye movements via a direct path, as well as through a modulating action on the central integrator. This influence of G load on the vestibular system could interfere with visual perception, and thereby play a role in inducing spatial disorientation.

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